Thermal Neutron Sensor Technology to Detect Illicit Nuclear Materials

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Micro- and nanotechnology advances are enabling a revolutionary new microscale, solid-state system for developing sensors to detect illicit special nuclear materials.

In the years since September 11, 2001, significant progress has been made to help ensure our country remains safe from any future attack. One scenario especially has haunted our national security planners: the detonation of an improvised radiological or nuclear device. As concerns about nuclear materials falling into the wrong hands have increased, so have efforts to develop new generations of sensors to detect these materials. One important research area seeks to improve the efficiency and adaptability of devices used to detect illicit special nuclear materials.

For many homeland security and nonproliferation efforts, semiconductor materials such as silicon can be used to custom-make 3-D microstructured sensors. Since nuclear materials release gamma and neutron energy, experts within Engineering's Center for Micro and Nano Technology (CMNT) are working to develop nano- and microsize sensing and detection devices for both types of radiation.

Neutron detectors are employed in a wide range of applications, including scanning air and ship cargoes, monitoring spent nuclear fuel, neutron imaging, monitoring ports of entry, and active interrogation of suspicious items. For certain applications, detectors must be inexpensive and robust, operate at ambient temperature, provide high detection efficiency, and be small enough for use in covert operations. Current detector technologies are limited in their ability to meet all of these requirements simultaneously. For example, many current gamma-ray detectors operate properly only at cryogenically cooled temperatures, a factor that significantly increases the overall system size. Devices used in the field for thermal neutron detection typically operate with tubes filled with Helium-3 (^{3}He) gas, a design with some inherent limitations. Such instruments are large, require high voltage to operate, and are sensitive to vibration. Additionally, ^{3}He is difficult to obtain and supplies of this important material are fast declining.

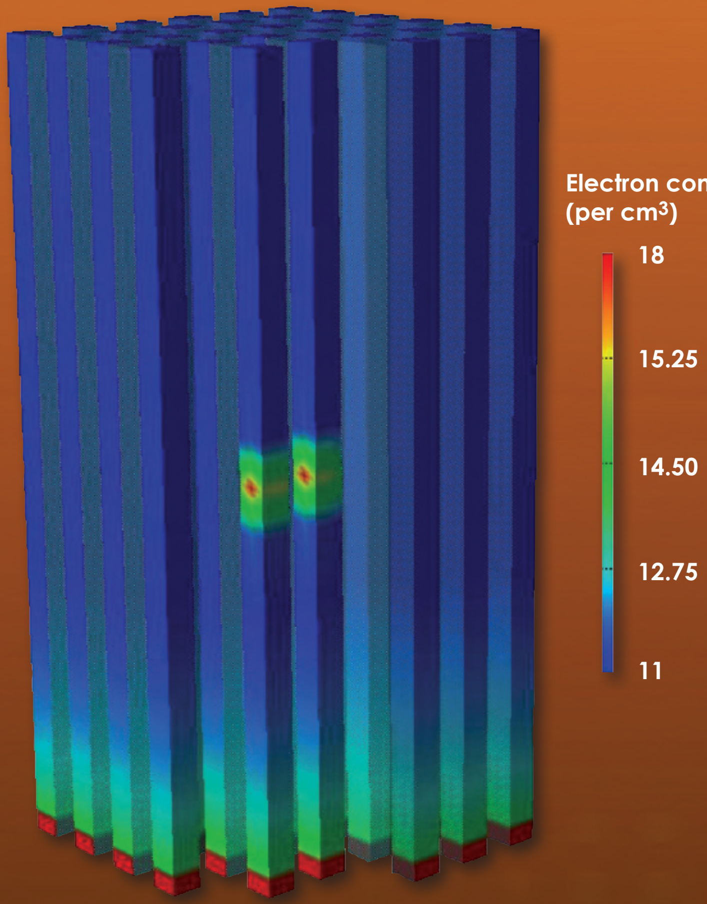

Figure 1. The simulated electron concentration in a 50-μm-tall pillar array 100 ps after the interaction of a neutron with the detector is shown (some areas have been removed for a better view of the interaction point).

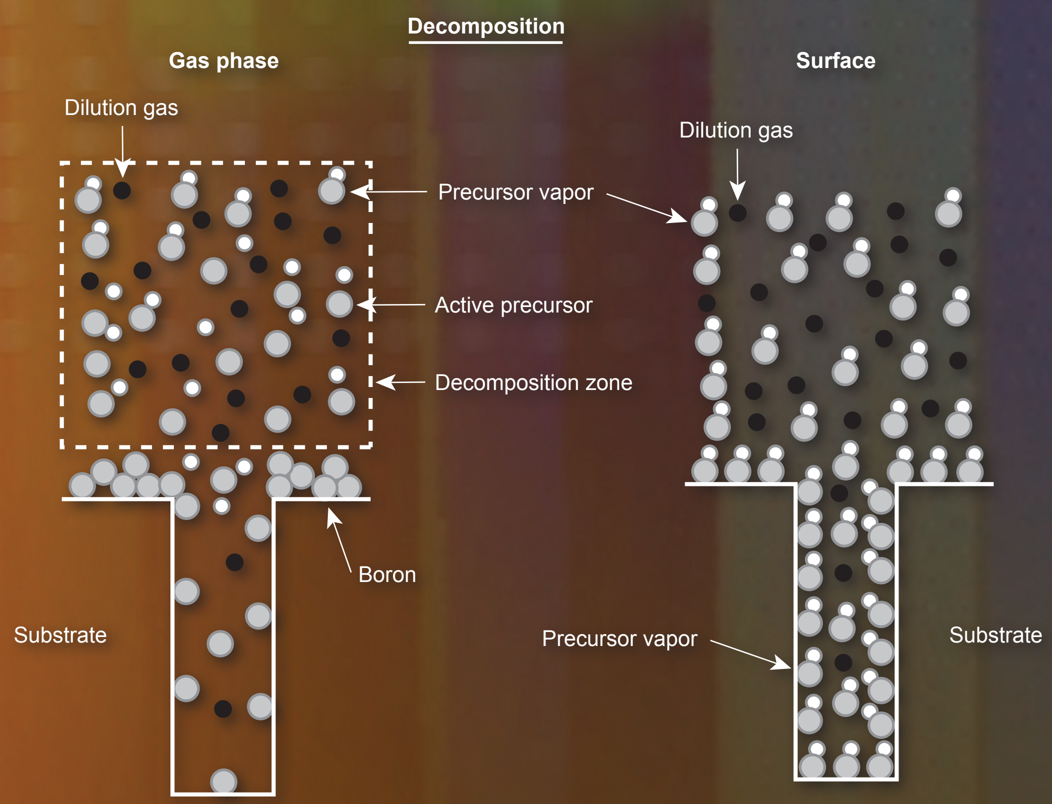

Figure 2. **Schematic drawing showing gas phase versus surface decomposition. Surface decomposition is needed for conformal coating of boron within the pillar array.**

Micro- and nanotechnology advances are enabling a revolutionary ^{3}He-tube replacement technology. A research team led by engineer Rebecca Nikolić has demonstrated that a microscale, solid-state system can be fabricated to produce high-efficiency thermal neutron detectors. The Livermore team's device, called the Pillar Detector, promises to achieve more than twice the efficiency of conventional thermal neutron detectors used in the field without the fieldability issues that challenge gaseous detectors.

Instead of gaseous ^{3}He, the Pillar Detector relies on a carefully constructed platform of 3-D etched silicon pillars that are interspersed with Boron-10 (^{10}B). We can adjust the pillar etch depth to provide a thicker boron layer for high neutron capture. We can also adjust the spacing between the pillars so the alpha particles don't have to travel far, which provides the device with high efficiency." The LLNL team is collaborating with the University of Nebraska at Lincoln, which uses chemical vapor deposition to fill the pillars with ^{10}B. Recently, the team demonstrated a thermal neutron efficiency of 20%, which is the largest efficiency reported to date for a semiconductor-based thermal neutron detector using ^{10}B as the converter material.

Designing the pillar-structured thermal neutron detector required understanding the complicated multi-step reactions that take place between a neutron striking the Pillar Detector and the current pulse that provides the electrical signal. Three different simulation tools were needed to unravel the physics that take place. A particle transport simulation (Figure 1) shows the electron concentration in a 50-µm-tall pillar array 100 ps after the interaction of a neutron with the detector. By combining results from multiple models, an optimized pillar structure was carefully designed. With the design established, the 3-D structure could be fabricated.

Conformal filling of high-aspect-ratio silicon micropillar structures with ^{10}B film was developed using low-pressure chemical vapor deposition (LPCVD) with decaborane. For this work, it was necessary for the ^{10}B to decompose on the surface of the pillar array instead of in the gas phase. If decomposition occurs in the gas phase, the boron coating will reside at the top of the pillars and a poor fill factor will result, as shown schematically in Figure 2. A high volume of ^{10}B is needed to efficiently capture the thermal neutrons.

Just as there was a lack of available processes for boron deposition, there was also a void in boron etching processes. Previous work to remove boron with plasmas had been reported, where plasmas were used to clean thermonuclear reactor chambers in which boron was used as a protective coating. In a similar vein, we developed an Electron Cyclotron Resonance (ECR) plasma etch approach based on fluorine chemistries. Figure 3 shows the processing progression to fabricate the Pillar Detector.

All fabrication steps successful

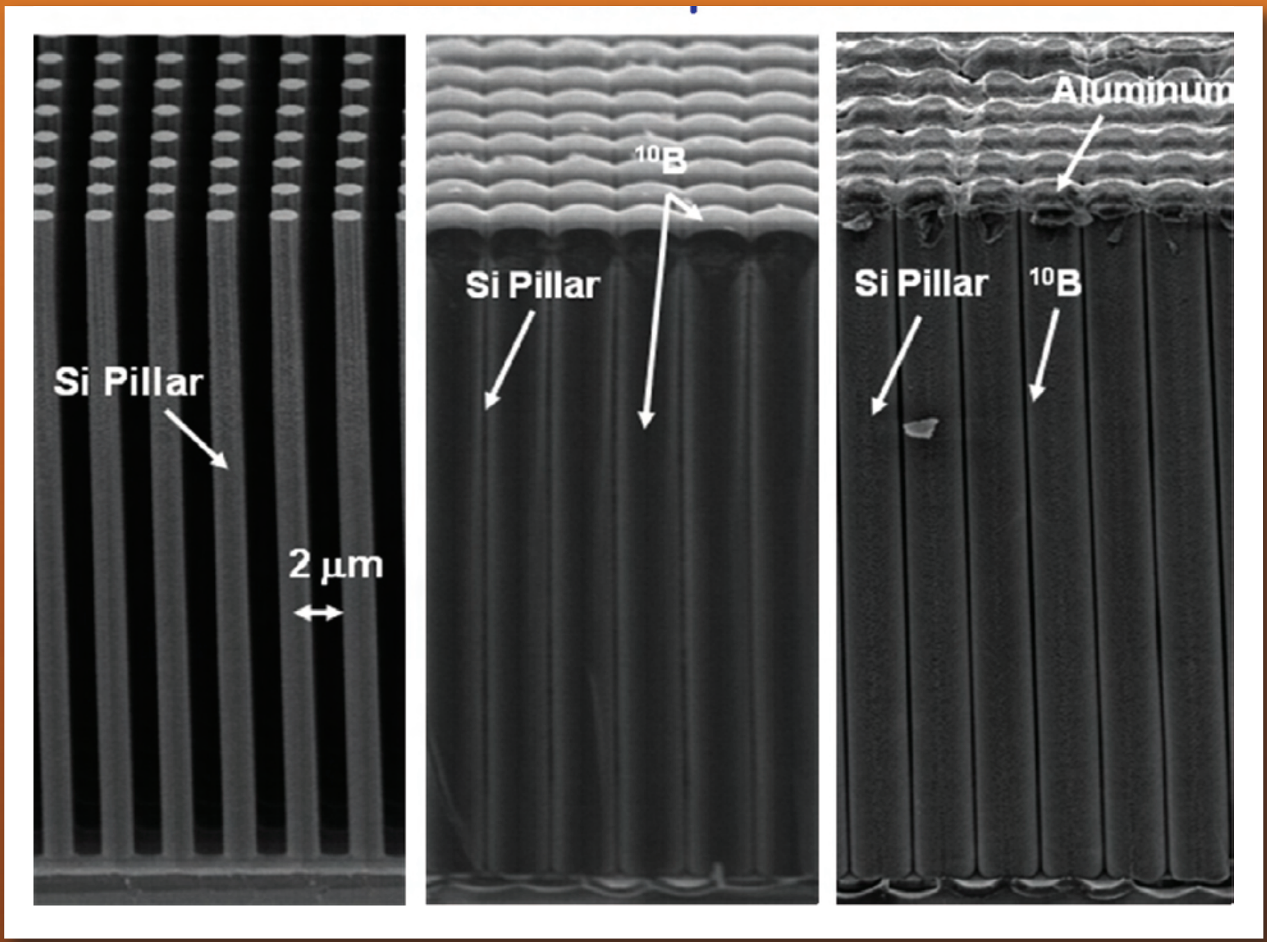

Figure 3. Progression of fabrication steps needed for the pillar processing.

Eventually, the LLNL pillar design is expected to provide over 50% efficiency and operate at low power (Figure 4). Because the silicon wafers can be cut to any size, a detector of any size can be produced, thus meeting the needs of many different end users. In almost every way, the three-dimensional silicon–boron wafer is superior to the ^{3}He tube. The wafer device requires less than three volts for operation, and newer designs may require even less. In addition, this highly effective detector will have less than 5 percent the physical volume of the standard ^{3}He detector for the same efficiency. The pillar-structured thermal neutron detector could prove to be the enabling technology for the next generation of radiation detection devices used as part of the effort to keep our homeland safe.

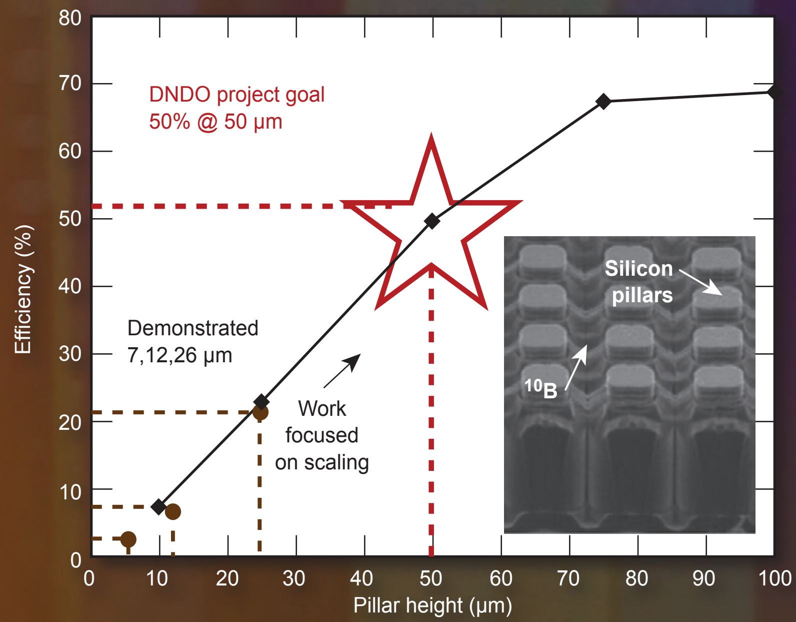

Figure 4. The team is now funded by the Department of Homeland Security to scale the device to 50% thermal neutron detection efficiency.